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**PERFORMANCE OF THE ELECTRICALLY-HEATED
2 TO 15 kWe BRAYTON POWER SYSTEM**

John L. Klann, Richard W. Vernon, David B. Fenn,
and Henry C. Block
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Fifth Intersociety Energy Conversion Engineering Conference
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Abstract

Initial results from two separate tests of the power conversion system are presented and compared to performance predictions. These results are based on 2250 hours of accumulated testing. About 1000 hours of that time was continuous operation at design temperatures in a vacuum-chamber test. No major technological problems were encountered in system operation.

With the design working gas mixture of helium and xenon and at design temperatures, a gross alternator power output up to 12 kilowatts was demonstrated in these initial tests. The corresponding measured power-conversion-system gross efficiency was 33 percent with an estimated net efficiency of 29 percent.

Measured conversion efficiencies with the gas mixture of helium and xenon were about 1 percentage point below the predicted level. Measured krypton efficiencies at design temperature exceeded predictions by about 2 percentage points.

Introduction

The NASA Brayton-cycle technology program for space power systems has advanced from component-level to system-level testing. The power system being investigated was described in the 1968 IECEC Conference (Ref. 1) and its status was updated in the 1969 conference by Brown (Ref. 2). Design conditions for the conversion equipment were selected (Ref. 3) for space use with a radioisotope heat source and a liquid-coolant radiator. The system has a design-life goal of 5 years.

Lewis Research Center is conducting two separate system tests. One is in an atmospheric environment. The other is in a vacuum chamber. In both of these initial system tests, the heat-source and heat-sink are simulated with test-support equipment. Electric heaters are used in place of an array of radioisotope capsules and, auxiliary heat exchangers cooled by facility refrigeration are used in place of a space radiator. The purpose of these tests is to map the performance of the conversion equipment and to demonstrate its endurance.

This paper presents initial results of the performance mapping. Measured levels of power conversion system performance are compared to those predicted by the method of Ref. 4. The main emphasis in this paper is on system performance. Other papers proposed for this conference cover more detailed component and subsystem performance. Thollot et al. (Ref. 5) covers the electrical subsystem; Kaykaty (Ref. 6), the heat exchangers; Thomas and Bilski (Ref. 7), the control system; Beremand and Wong (Ref. 8), the rotating machinery assembly; Ingle and Winner (Ref. 9), the alternator and its controls; and Gilbert and Perz (Ref. 10) on the alternator power requirements and harmonic distortion.

Test Hardware

A schematic diagram of the power system is presented in Figure 1. The components included in the gas loop are the source heat exchanger, the Brayton rotating unit (BRU), and the Brayton heat exchanger unit (BHXU). The required subsystems are: heat source, gas management, electrical, and the heat rejection subsystem.

With the exception of the actual configuration of the heat source and heat sink, the system tested in a vacuum environment represents a close-coupled arrangement of flight-type hardware. The purpose of the vacuum tests is to demonstrate performance capability of a complete self-contained power system of flight-type hardware. These tests are being conducted in the Space Power Facility, Plum Brook Station, Lewis Research Center. Initial performance of the system using krypton as the working gas is reported in Ref. 11.

The purpose of the tests conducted in an atmospheric environment

is mainly to demonstrate endurance capability of the BRU, and the BHXU. The remainder of the hardware in the atmospheric test is support-type equipment. These tests are being conducted at the Lewis Research Center, Cleveland, Ohio. Performance of the system using krypton as the working gas is presented in Ref. 12.

Identical BRU's and BHXU's are used in both systems being tested. These components are arranged identically in both tests.

Brayton Rotating Unit (BRU)

The rotating unit includes three components: a turbine, a compressor, and an alternator. All three components are mounted on a common shaft. The journal and thrust bearings that support the shaft are lubricated by the working gas. Design rotational speed of the shaft is 36 000 rpm. In both test facilities the BRU was mounted with the shaft vertical, turbine-end up.

The alternator is designed to produce 120 volts (line-to-neutral), 208 volts (line-to-line) electrical power at a frequency of 1200 Hertz. Redundant coolant passages are provided to cool the alternator.

Brayton Heat Exchanger Unit (BHXU)

The heat exchanger unit includes a recuperator, waste heat exchanger, and necessary ducting. The recuperator is a gas-to-gas counterflow unit. The waste heat exchanger is a gas-to-liquid cross-counterflow unit. Plate and finned-surface construction is used for all flow passages. The waste heat exchanger has redundant coolant passages. Only one passage was used at any time for either test.

Gas Management Subsystem

This subsystem supplies working fluid for gas injection starts and hydrostatic support of the BRU bearings during start-ups and shut-downs. It also provides for gas loop pressure changes.

Electrical Subsystem

The electrical subsystem provides regulation of alternator output voltage and BRU shaft speed. This subsystem also provides for distribution of alternator power among the user's load bus, a parasitic load resistor, and a dc power supply for engine housekeeping power.

Included in the electrical subsystem is the engine control system. This system provides control to start, run, and shut down the engine. In addition, protection is provided against electrical overload and component malfunctions.

Heat Rejection Subsystem

A silicone liquid is used as the coolant. The liquid is circulated through the alternator and the waste heat exchanger.

For the vacuum tests the components of the electrical subsystem were mounted on the cold plate heat exchangers. The coolant was circulated through the cold plates in parallel with the alternator and waste heat exchanger. In the atmospheric environment tests, electrical components were cooled by fans.

In both tests, waste thermal energy was removed from the coolant by facility refrigeration systems.

Heat Source Subsystem

For the vacuum tests the heat source was a bank of radiantly heated U-tubes centrally located in the heat exchanger. The gas flows through the U-tubes. The atmospheric data were obtained using a heat source containing 500 resistance-heated tubes within the gas stream. The gas flowed perpendicular to the axis of the tubes which were arranged in a compact staggered array.

Design Conditions

The power conversion system was designed for the use of a mixture of helium and xenon at the molecular weight of krypton, 83.8. Its design turbine-inlet temperature was 1600° F, and design compressor-inlet temperature was 80° F. Its design operational range in compressor-outlet pressure, from 14 to 45 psia, was intended to provide gross alternator power outputs from 2.25 to 10.5 kilowatts at the design temperatures.

Performance Calculations

Power conversion system performance is presented in terms of its gross power and efficiency. Gross output power is that measured at the alternator terminals. Gross power neglects housekeeping electrical power needs and any user-power-conditioning needs. Gross efficiency is the ratio of alternator power output to the thermal power added to the power conversion system gas. This added thermal power is defined as the product of the gas mass-flow rate, the ideal-gas specific heat at constant pressure, and the temperature difference between stations 1 and 6 in Fig. 1. Hence, power conversion system gross efficiency also neglects heat-source-subsystem thermal losses.

For a flight-type electrical system, the housekeeping power needs are estimated to be 1.4 kilowatts (Ref. 5). Hence, estimated net output power is 1.4 kilowatts less than the gross alternator power. Power conversion system net efficiency is the ratio of the estimated net output to the thermal power added to the power conversion system gas. In space use, overall Brayton power system efficiency would be obtained from the product of heat-source subsystem efficiency, net power conversion system efficiency, and user power conditioning efficiency.

Measured performance is compared to that predicted by the digital computer program described in Ref. 4. The computer program synthesized the operation of the ground-test power system from component performance. Computed levels of performance from this program must be considered ideal, mainly because heat losses from the system were neglected.

Operating Experience

As of May 15, 1970, a total of 2250 hours of power system operation had been accumulated from the combined atmospheric and vacuum testing. No major technological problems were encountered. However, procedural errors in the early system testing led to the damage of two rotating machinery assemblies (BRU). One BRU was damaged when the alternator-field excitation was inadvertently turned off through a manual switch. This occurred in the atmospheric testing before initial steady-state conditions were reached. The other damaged BRU resulted from a poor initial choice of solder in the wiring harness for the vacuum tests. Corrective action was taken and no repetition has occurred.

Table I shows a breakdown of the accumulated test hours. Most data to date was obtained in the vacuum-chamber tests. Initial checkouts in both tests used krypton as the working gas. A total of 584 hours was logged with krypton in the vacuum tests. However, because of early problems with the electric heat source, these data were limited to a maximum temperature of about 1400° F. Test data with BRU-1 and the helium-xenon mixture were obtained with a modified electric heat source up to a turbine-inlet temperature of 1500° F. Design performance data has been obtained with BRU-2. Of the total hours on BRU-2, 1176 hours were continuous testing with about 1050 hours of that at 1600° F.

The atmospheric-environment tests have completed the initial checkouts and performance mapping with krypton. Design values of turbine-inlet temperature were obtained. However, because of alternator heating (Refs. 4 and 13) the range in pressure level was not completely mapped at the design temperatures.

Performance Results

Performance mapping of the Brayton power conversion system covers ranges of interest in its three independent parameters: turbine-inlet temperature, compressor-inlet temperature, and com-

pressor outlet pressure. This paper presents initial results of such performance mapping. The majority of data which are presented were obtained from testing up to the end of February, 1970. This includes the BRU-1, vacuum-chamber data and the atmospheric-environment data summarized in Table I. Design-temperature data obtained with helium-xenon and BRU-2 in the vacuum-chamber tests are also included.

Design Conditions

Figure 2 shows the effect of compressor-outlet pressure on gross output and efficiency at the design inlet temperatures. The data were obtained in the vacuum-chamber tests with the working gas mixture of helium and xenon. Measured alternator power increased from about 6 kilowatts at 25 psia to about 12 kilowatts at 44 psia. Power conversion system gross efficiency increased from about 0.30 to about 0.33 over the same pressure range. Estimated net efficiency at 12 kilowatts of gross power is about 29 percent. Gross power measurements were in good agreement with the computer predictions. Measured gross efficiency was about 1-percentage point below the predicted level.

The highest power output which has been demonstrated in any of these early tests is 12 kilowatts. Although 15 kilowatts of output has not yet been reached in these system tests, operation at this high-power level was shown to be feasible, with additional cooling, in a separate test of the rotating machinery assembly (Ref. 13). Current plans are to add liquid-coolant passages in the area of the alternator end-turns to provide more cooling for normal operations.

Turbine-Inlet Temperature Effects

Figure 3 presents the effect of turbine-inlet temperature on gross output and efficiency at a compressor-outlet pressure of 29 psia. Both atmospheric and vacuum-test data are shown. The working gas was krypton and the compressor-inlet temperature was 80° F.

Since there was essentially no difference between the performance in air and vacuum, only one solid line was faired through the data. Measured gross power increased from 3.4 kilowatts at 1200° F to 7.7 kilowatts at 1600° F. Gross efficiency increased from 0.17 to 0.32. The performance levels of these results were about as expected based on the predicted values. However, the data show a slightly increased sensitivity to change with turbine-inlet temperature than the predictions. If needed, the Brayton power conversion system can be operated at lower-than-design turbine-inlet temperatures. Operation has been demonstrated down to 1200° F, or 400° F below design. The data of Fig. 3 show the power penalties of reduced turbine-inlet temperature at a compressor-outlet pressure of 29 psia. Gross alternator power decreased by about 1.1 kilowatts per 100° F-reduction in turbine-inlet temperature, while gross efficiency decreased by about 4 percentage points per 100° F. Although this sensitivity was based on krypton results at a mid-design pressure level, it is about the average sensitivity for the effect of turbine-inlet temperature at other pressure levels within the range from 25 to 44 psia and for either gas.

Compressor-Inlet Temperature Effects

Figure 4 shows effects of compressor-inlet temperature on gross performance. The data were obtained in the vacuum tests with krypton as the working gas. Turbine-inlet temperature was about 1300° F, while compressor-outlet pressure was about 25 psia. Corresponding predicted values of gross power and efficiency are shown by the dashed lines. The data show a range in compressor-inlet temperatures from about 40° to 100° F. Rates of change in gross power and efficiency with temperature were the same for both the measured results and predicted values. A 10° increase in compressor-inlet temperature resulted in a 0.3-kilowatt decrease in power output and a 0.012-decrease in efficiency. This sensitivity to compressor-inlet temperature is about the same for either working gas at any value of turbine-inlet temperature up to and including 1600° F.

In space use the operating range in compressor-inlet temperature is dependent on radiator area. And although performance improves with decreasing compressor-inlet temperature, larger radi-

ators would be needed to obtain them.

Working Gas Comparison

The design working gas mixture of helium and xenon was selected to have the same average molecular weight as that of krypton. These gases also have about the same viscosity. Therefore, the fluid-dynamic performance within the rotating machinery should be identical. And the alternator power output with either of these gases should be the same for equal temperature and pressure conditions. However, the thermal conductivity of krypton is about 0.4 that of the gas mixture. Heat-transfer performance and gross efficiency is expected to be better with the mixture. Less thermal input power should be required for the same alternator output with the mixture than with krypton. At design temperatures, Ref. 4 shows that ideally from a 1- to 3-percentage-point improvement in efficiency should be expected.

An off-design turbine-inlet temperature comparison among test data is shown in Table II. Krypton results from the vacuum-chamber tests are shown in column 1, while similar helium-xenon results are shown in the other two columns.

Initial gas mixture performance (BRU-1 in Table II) showed less power output and about the same efficiency compared to krypton. Preliminary analysis has not resulted in a conclusive reason for this lower performance. The BRU-2, helium-xenon results did show the same power output as krypton and about a 1-percentage-point improvement in efficiency. Based on the predictions, about a 2-percentage-point efficiency gain was expected.

A further comparison is shown in Table III. Atmospheric- and vacuum-test data are shown. The data is for the highest-power-output conditions attained to date in both tests. In the atmospheric tests with krypton a power level of about 10 kilowatts was reached at 35.4 psia; while the 12-kilowatt, vacuum data for helium-xenon is repeated from Fig. 2. The measured gross efficiencies were about the same. However, because of the lower power level with krypton the estimated net efficiencies with helium-xenon was about 1 percentage point higher. Comparison between measured and predicted gross efficiencies shows that the krypton data exceeded the predicted level by about 2 percentage points, while the helium-xenon data was about 1 percentage point lower than predicted.

Although these comparisons do not indicate as much of an efficiency advantage for the gas mixture over krypton as was predicted, a firm conclusion cannot yet be reached. More comparative testing is needed on the same configuration in the same facility.

The potential 3-percentage-point gain (Ref. 4) over krypton performance is particularly important with the use of a radioisotope heat source. At the 30-percent-efficiency level, a 3-percentage-point gain would result in about a 9-percent saving in the required amount of radioisotopes. Also there would be savings in heat-source size and weight.

Concluding Remarks

A total of 2250 hours of testing was conducted on two separate electrically-heated Brayton power systems. About 1000 hours of continuous operation at design temperatures was demonstrated in the vacuum-chamber tests. No major technological problems have been encountered in the operation of these systems.

At design temperatures with the design helium-xenon working gas mixture, a gross alternator power output up to 12 kilowatts was demonstrated in these initial tests. At this power level the measured power-conversion-system gross efficiency was 33 percent with an estimated net efficiency of 29 percent. These efficiencies were 1-percentage point below the predicted values. Demonstration of these high levels of conversion efficiency in the ground testing means that we can more confidently expect high performance in space use. Overall Brayton space-power-system efficiencies, including heat-source losses and additional user-power-conditioning losses, in the mid-20-percent range should be achievable.

No firm conclusion can be reached from these early tests on the predicted efficiency advantage of the design gas mixture over that of

krypton. Both gases have resulted in the 33-percent-conversion-efficiency level at design temperatures. However, these measurements were made in different facilities and at different power levels so that a strict comparison cannot yet be made.

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TABLE I. - TEST SUMMARY - ACCUMULATED HOURS
AS OF MAY 15, 1970

	Hours with krypton	Hours with helium-xenon	Total hours
Vacuum-chamber tests			
With BRU-1	584	84	668
With BRU-2	0	1374	<u>1374</u>
			2042
Atmospheric-environment tests	210	0	<u>210</u>
			2252

TABLE II. - COMPARISON AMONG KRYPTON AND HELIUM-XENON
DATA FROM VACUUM-CHAMBER TESTS

	BRU-1		BRU-2
Working gas	Kr	He-Xe	He-Xe
Turbine-inlet temperature, °F	1395	1397	1396
Compressor-inlet temperature, °F	82	83	85
Compressor-outlet pressure, psia	39.8	40.1	40.0
Gross alternator power, kW	8.00	7.48	7.97
(Predicted value ^a)	(8.61)	(8.61)	(8.61)
Gross efficiency	0.254	0.253	0.263
(Predicted value ^a)	(0.267)	(0.289)	(0.289)

^aComputer predictions for 1400° F, turbine-inlet and 80° F, compressor inlet.

TABLE III. - COMPARISON BETWEEN GASES AND
TEST ENVIRONMENT

Test environment	Vacuum	Atmospheric
Working gas	He/Xe	Kr
Turbine-inlet temperature, °F	1607	1609
Compressor-inlet temperature, °F	81	80
Compressor-outlet pressure, psia	44.2	35.4
Gross alternator power, kW	12.0	9.88
(Predicted value ^a)	(12.1)	(9.44)
Gross efficiency	0.326	0.327
(Predicted value ^a)	(0.336)	(0.308)
Estimated net power, kW	10.55	8.48
Estimated net efficiency	0.288	0.281

^aComputer predictions for 1400° F, turbine-inlet and 80° F, compressor inlet.

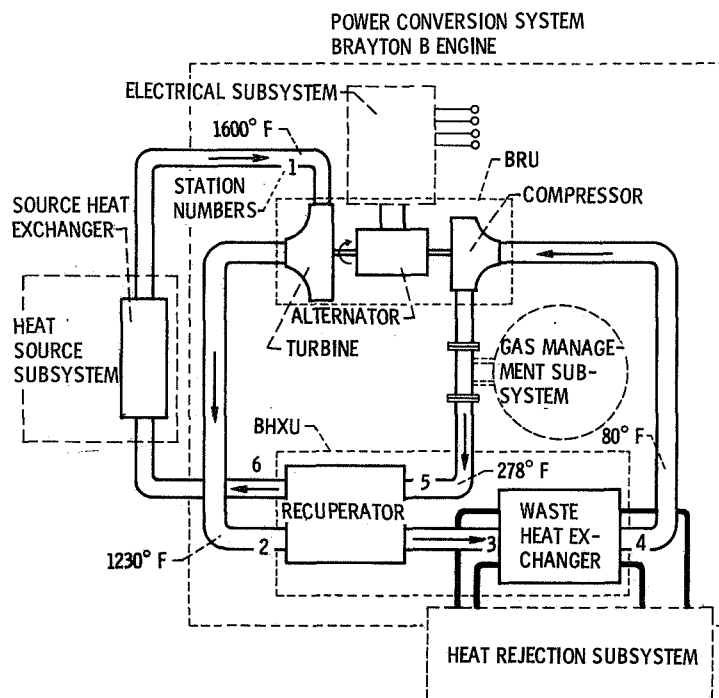


Figure 1. - Schematic diagram, Brayton power system.

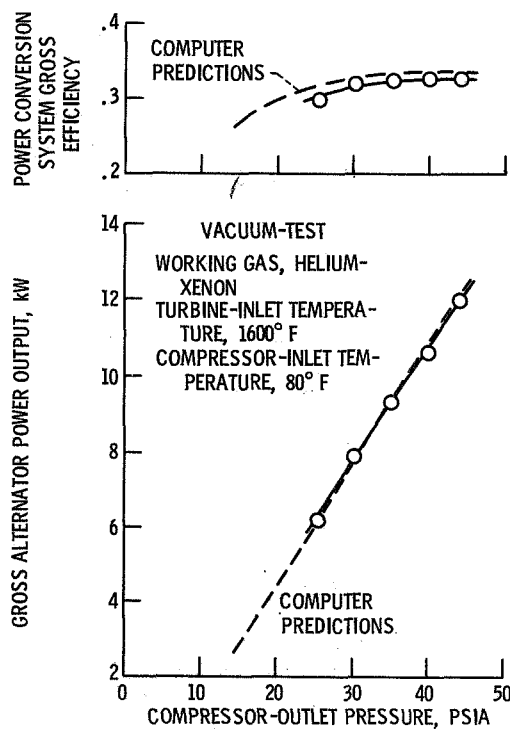


Figure 2. - Compressor-outlet pressure effect on power conversion system gross performance. Design operating conditions.

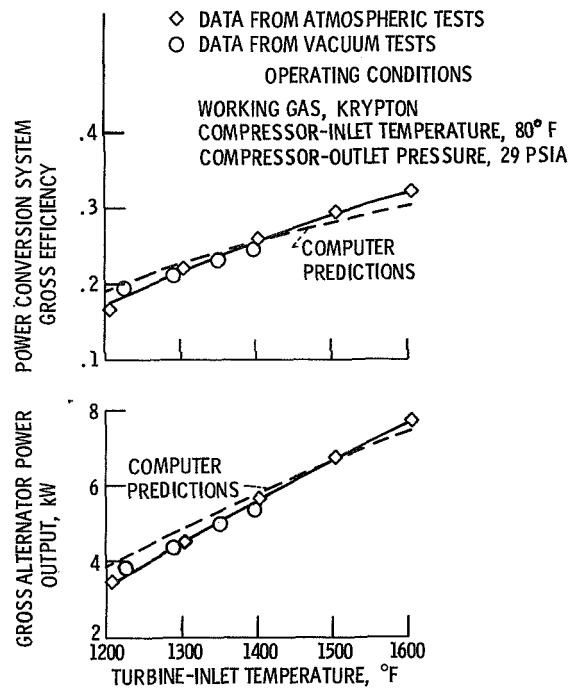


Figure 3. - Turbine-inlet temperature effect on power conversion system gross performance.

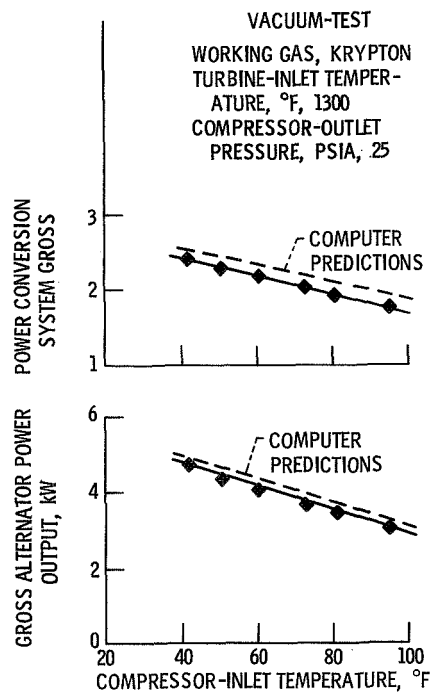


Figure 4. - Compressor-inlet temperature effect on power conversion system gross performance.